

NONLEPTONIC CHARM DECAYS AND CP VIOLATION

BHUBANJYOTI BHATTACHARYA¹

*Physique des Particules, Université de Montréal
 C.P. 6128, succ. centre-ville, Montréal, QC, Canada H3C 3J7*

MICHAEL GRONAU

*Physics Department, Technion – Israel Institute of Technology
 Haifa 32000, Israel*

JONATHAN L. ROSNER

*Enrico Fermi Institute and Department of Physics
 University of Chicago, 5620 S. Ellis Avenue, Chicago, IL 60637*

In this talk we briefly present a flavor-SU(3) technique to study branching ratios and direct CP asymmetries of D -meson decays. The first part of the talk is meant to set up a foundation, based on previous work, to deal with flavor-SU(3) amplitudes and relative strong phases. In addition, we present a model for dealing with SU(3)-breaking in branching ratio measurements of SCS D^0 decays. In the second part of the talk we make use of a proposal for an enhanced CP-violating penguin in the SM, to explain the recent LHCb and CDF observations of CP violation in SCS D^0 decays. Furthermore, we use our model to predict CP violation in $\pi^0\pi^0$ and $K^+\bar{K}^0$ final states. Large experimental bounds on individual CP asymmetries give rise to a large allowed range of δ , the strong phase of the CP-violating penguin. We also briefly discuss future prospects.

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¹Speaker

I Introduction: Why study charm?

Experiments worldwide are looking for signatures of new physics beyond the Standard Model (SM). While most searches are dedicated to energy frontiers, if new physics is present, there is a high chance that it may rear its head at low energies in B and D meson decays. In order for new physics searches at low energies to be successful, however, it is necessary to rule out the possibility that the observed signals may have been produced by SM processes that are yet not understood, so that indeed the signal is new physics. Thus, a good place to look for new physics is where the expected SM signals are suppressed, so that it is easier to distinguish a new physics signal from the expected SM background.

Charm physics is dominated by the first two generations of quarks and the associated elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix in the SM. These matrix elements are relatively large compared to those also involving the third generation of quarks. Furthermore, since the charm mass is quite close to the scale at which perturbative QCD breaks down (Λ_{QCD}), one expects non-perturbative effects to cause unforeseen enhancements [1]. Due to these reasons one might think that nothing new can be observed in charm physics. However, processes involving charm also depend on the suppressed elements in the CKM matrix associated with the third generation of quarks via CKM unitarity constraints. Utilizing this fact, one may still be able to use charm physics as a possible source for new physics signals, in particular in studies of CP violation in charmed meson decays.

Earlier the CDF collaboration had measured time-integrated CP asymmetries in D^0 decays to K^+K^- and $\pi^+\pi^-$ final states [2], and found them to be consistent with zero. Recently, however, the LHCb collaboration found 3.5σ evidence for direct CP violation in singly-Cabibbo-suppressed (SCS) D decays [3]. LHCb measured the difference between direct CP asymmetries in the above channels, and found it to be approaching the percent level. This has brought charm physics into the limelight as a potential source for new physics signals. Based on the LHCb result, CDF has presented an updated analysis [4]. The joint LHCb and CDF results now measure almost a -0.7% difference in CP asymmetries in the two channels. SCS D decays in particular have thus recently received an increased amount of attention. Many authors have proposed models that involve new physics at an appropriately high mass scale, that may be responsible for a large observed direct CP asymmetry [5–12]. These models also include additional ways of testing their validity. Some authors, however, have proposed a more cautious line of thought, arguing that non-perturbative enhancements in SM amplitudes can't be ruled out and may be responsible for the large observed CP violation [13–17]. We studied the phenomenological consequences of such an enhanced penguin in Refs. [18, 19].

We begin by briefly discussing the technique of applying flavor-SU(3) symmetry to study charm decays. Sec. II presents a discussion of branching fractions in Cabibbo-favored (CF) D decays, studied in the light of flavor-SU(3) symmetry. We discuss a model for studying flavor-SU(3) breaking in SCS decays and also discuss D decays to a pseudoscalar (P) and a vector (V) meson. In Sec. III we discuss our model based on a phenomenological CP-violating penguin amplitude, required to explain the LHCb and CDF observations. We also discuss the possibility of measuring similar sub-percent level CP asymmetries in other D^0 and D^+ decay channels. We present our conclusions in Sec. IV.

II Branching fractions in decays of D mesons

A Flavor SU(3) diagrammatics

In this section we review the basics of flavor-SU(3) diagrammatics. Cabibbo-favored (CF) decays are described in terms of tree-level topologies “Color-favored Tree” (T), “Color-suppressed Tree” (C), “Exchange” (E) and “Annihilation” (A). The quark-level transition $c \rightarrow su\bar{d}$ does not allow penguin topologies. In order to describe singly-Cabibbo-suppressed (SCS) D decays, in addition to tree-level topologies we also need “Penguin” (P) and “Penguin Annihilation” (PA) topologies associated with the quark-level transitions $c \rightarrow du\bar{d}$ and $c \rightarrow su\bar{s}$. Furthermore, in order to account for flavor-SU(3) breaking in SCS processes, we include factorizable SU(3)-breaking in T and A amplitudes, as described originally in Ref. [18] and outlined in the following expressions:

$$T_{D^0 \rightarrow \pi^+ \pi^-} = T_{D^+ \rightarrow \pi^+ \pi^0} = T_{D_s^+ \rightarrow \pi^+ K^0} = T_\pi, \quad (1)$$

$$T_{D^0 \rightarrow K^+ K^-} = T_{D^+ \rightarrow K^+ \bar{K}^0} = T_K, \quad (2)$$

$$A_{D_s^+ \rightarrow \pi^+ K^0} = A_{D_s^+ \rightarrow K^+ \pi^0} = A, \quad (3)$$

$$A_{D^+ \rightarrow K^+ \bar{K}^0} = A_{D^+} = A \cdot \frac{f_{D^+}}{f_{D_s^+}}. \quad (4)$$

where, $T_{\pi,K}$ are obtained in terms of known parameters, namely the CF T [20], relevant form factors [21, 22], decay constants [23] and meson masses [24], as follows:

$$T_\pi = T \cdot \frac{|f_{+(D^0 \rightarrow \pi^-)}(m_\pi^2)|}{|f_{+(D^0 \rightarrow K^-)}(m_\pi^2)|} \cdot \frac{m_D^2 - m_\pi^2}{m_D^2 - m_K^2}, \quad (5)$$

$$T_K = T \cdot \frac{|f_{+(D^0 \rightarrow K^-)}(m_K^2)|}{|f_{+(D^0 \rightarrow K^-)}(m_\pi^2)|} \cdot \frac{f_K}{f_\pi}. \quad (6)$$

Tree-level topologies in CF-decay amplitudes are proportional to a CKM factor $V_{cs}^* V_{ud} \sim 1$, while those in SCS-decay amplitudes come with a factor of $V_{cd}^* V_{ud} \sim -\lambda$ or $V_{cs}^* V_{us} \sim \lambda$ (we neglect the weak-phase difference between these quantities that shows up at a higher order in λ). Here we use $\lambda = \tan \theta_C = 0.2317$ [24].

Each relevant penguin amplitude gets contributions from all three down-type quarks running in the loop. Therefore, unlike the tree topologies, penguin topologies depend on more than one CKM factors. However, unitarity of the CKM matrix tells us that these CKM factors are not completely independent, but that they obey the relationship:

$$V_{cd}^* V_{ud} + V_{cd}^* V_{ud} + V_{cb}^* V_{ub} = 0. \quad (7)$$

Using CKM unitarity, thus, it is possible to eliminate one of the CKM factors as follows:

$$\sum_q V_{cq}^* V_{uq} \mathcal{P}_q = V_{cs}^* V_{us} (\mathcal{P}_s - \mathcal{P}_d) + V_{cb}^* V_{ub} (\mathcal{P}_b - \mathcal{P}_d), \quad (8)$$

$$= P + P_b, \quad (9)$$

where the index q denotes the quark running in the loop, and \mathcal{P} denotes the reduced matrix element corresponding to the penguin topology denoted by P . Thus, in the last line we have used the following definitions of the variables:

$$V_{cs}^* V_{us} (\mathcal{P}_s - \mathcal{P}_d) \equiv P, \quad (10)$$

$$V_{cb}^* V_{ub} (\mathcal{P}_b - \mathcal{P}_d) \equiv P_b. \quad (11)$$

Table I: Representations and comparison of experimental and fit branching fractions for CF decays of charmed mesons to two pseudoscalars [20].

Meson	Mode	Rep.(\mathcal{A})	\mathcal{B} (%)	Fit \mathcal{B} (%)
D^0	$K^-\pi^+$	$T + E$	3.89 ± 0.08	3.91
	$\bar{K}^0\pi^0$	$(C - E)/\sqrt{2}$	2.38 ± 0.09	2.35
	$\bar{K}^0\eta$	$C/\sqrt{3}$	0.96 ± 0.06	1.00
	$\bar{K}^0\eta'$	$-(C + 3E)/\sqrt{6}$	1.90 ± 0.11	1.92
D^+	$\bar{K}^0\pi^+$	$C + T$	3.07 ± 0.10	3.09
D_s^+	$\bar{K}^0 K^+$	$C + A$	2.98 ± 0.17	2.94
	$\pi^+\eta$	$(T - 2A)/\sqrt{3}$	1.84 ± 0.15	1.81
	$\pi^+\eta'$	$2(T + A)/\sqrt{6}$	3.95 ± 0.34	3.60

We now note that the magnitude of P_b is largely suppressed due to the CKM factor $V_{cb}^* V_{ub} \sim \mathcal{O}(\lambda^5)$ when compared to the magnitude of P . Thus, in a discussion solely concerning branching fractions of D decays it is justified to neglect P_b . However, P_b is relevant in the discussion of direct CP asymmetries, as we shall see later.

B $D \rightarrow PP$ decays

CF D decays to a pair of pseudoscalars were examined in detail in Refs. [20, 25–27]. In short, there are eight decay rates that depend on four complex amplitudes and three relative strong phases. In Ref. [20], a χ^2 -minimization fit was used to obtain these parameters. The ($|T| > |C|$) solution obtained in this fit is:

$$T = 2.927, \quad (12)$$

$$C = 2.337 e^{-i 151.66^\circ} = -2.057 - 1.109 i, \quad (13)$$

$$E = 1.573 e^{i 120.56^\circ} = -0.800 + 1.355 i, \quad (14)$$

$$A = 0.33 e^{i 70.47^\circ} = 0.110 + 0.311 i, \quad (15)$$

in units of 10^{-6} GeV. The minimum value for χ^2 was found to be 1.79 for one degree of freedom, indicating that the fit was reasonable. In Table I we list the CF decay modes and their flavor-topology representations, alongside the observed and fitted branching fractions for comparison.

Although the flavor-SU(3) parameters fit quite reasonably the decay rates of CF D decays to a pair of pseudoscalars, in order to describe SCS decays, however, one needs to include the effects of flavor-SU(3) breaking. The necessity to include SU(3)-breaking effects can be illustrated by considering the SCS processes $D^0 \rightarrow \pi^+\pi^-, K^+K^-, K^0\bar{K}^0$. Although under flavor SU(3) the amplitudes for the first two processes are the expected to be identical, in practice both these amplitudes differ from their predicted value. Furthermore the amplitude for the third processes is predicted to vanish under flavor SU(3), yet in practice it is significantly different from zero.

As a qualitative explanation to SU(3)-breaking in $D^0 \rightarrow \pi^+\pi^-, K^+K^-$, ratios of form factors and decay constants have been used, since the amplitudes for these processes are

Table II: Representations and comparison of experimental and fit amplitudes for SCS decays of charmed mesons to two pseudoscalar mesons. Also listed are individual χ^2 contribution and overall strong phase (ϕ_T^f) for each process [18].

Decay Mode	Amplitude representation	$ \mathcal{A} $ (10^{-7} GeV)		χ^2	ϕ_T^f degrees
		Experiment	Theory		
$D^0 \rightarrow \pi^+\pi^-$	$-\lambda(T_\pi + E) + (P + PA)$	4.70 ± 0.08	4.70	0	-158.5
$D^0 \rightarrow K^+K^-$	$\lambda(T_K + E) + (P + PA)$	8.49 ± 0.10	8.48	0.01	32.5
$D^0 \rightarrow \pi^0\pi^0$	$-\lambda(C - E)/\sqrt{2} - (P + PA)/\sqrt{2}$	3.51 ± 0.11	3.51	0	60.0
$D^+ \rightarrow \pi^+\pi^0$	$-\lambda(T_\pi + C)/\sqrt{2}$	2.66 ± 0.07	2.26	33	126.3
$D^0 \rightarrow K^0\bar{K}^0$	$-(P + PA) + P$	2.39 ± 0.14	2.37	0.02	-145.6
$D^+ \rightarrow K^+\bar{K}^0$	$\lambda(T_K - A_{D^+}) + P$	6.55 ± 0.12	6.87	7	-4.2
$D_s^+ \rightarrow \pi^+K^0$	$-\lambda(T_\pi - A) + P$	5.94 ± 0.32	7.96	40	174.3
$D_s^+ \rightarrow \pi^0K^+$	$-\lambda(C + A)/\sqrt{2} - P/\sqrt{2}$	2.94 ± 0.55	4.44	7	16.4

largely dominated by T which is expected to follow factorization. However, as discussed in Ref. [18], corrections to T using factorization fail to explain the discrepancy between theory and experiment. This can be remedied by adding the ordinarily GIM-suppressed [28] P and PA topologies, the magnitude and strong phase of which may then be obtained by fitting to the SCS D -decay rates.

In Table II, we present the SCS decay modes and their flavor-topology representations, alongside the observed and fitted amplitudes for comparison. Also listed in Table II is the overall strong phase (ϕ_T^f) for each final state f . (The index T refers to the CP-conserving nature of the amplitude, that is, it has the same weak phase as the tree-level contributions.) The decay rates for $D^0 \rightarrow (\pi^+\pi^-, \pi^0\pi^0, K^+K^-)$ depend only on the combination $P + PA$, while those for $D^0 \rightarrow K^0\bar{K}^0, D^+ \rightarrow K^+\bar{K}^0, D_s^+ \rightarrow \pi^+K^0, \pi^0K^+$ depend only on P . We perform χ^2 minimization fits and obtain the following results for $P + PA$ and P :

$$P + PA = [(0.44 \pm 0.23) + (1.41 \pm 0.36) i] \times 10^{-7} \text{ GeV} ; \quad (16)$$

$$\chi^2/\text{d.o.f.} = 0.012/1 = 0.012 . \quad (17)$$

$$P = [(-1.52 \pm 0.15) + (0.08_{-0.32}^{+0.38}) i] \times 10^{-7} \text{ GeV} ; \quad (18)$$

$$\chi^2/\text{d.o.f.} = 54/2 = 27 . \quad (19)$$

The χ^2 contribution for each process has also been listed in Table II.

The χ^2 minimum solution obtained for $P + PA$ above supports the existence of a self-consistent solution in terms of a construction technique described in [18]. We briefly revisit the idea. Let us consider the three decays that depend only on the combination $P + PA$. The representations for these three amplitudes have been listed in the first three rows of Table II. One can rewrite the representations such that the coefficient of $P + PA$ is always one. One part of these amplitudes can be calculated from the CF-decay parameters (including factorizable SU(3) breaking in the T diagram). We first construct vectors on the complex plane to represent these. With the heads of these vectors as the centers we draw circles with radii equal to the respective measured amplitudes and their $\pm 1\sigma$ error bands. We identify the best-possible intersection point of the circles representing the three different

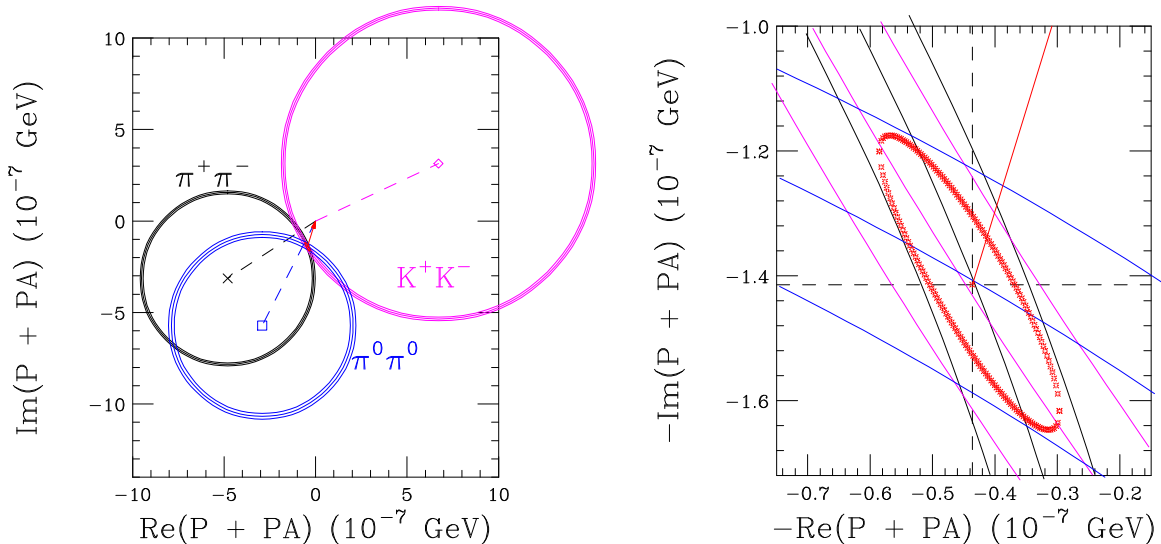


Figure 1: Construction to determine $P + PA$. The relative sign between the left-hand and (magnified) right-hand panels is due to the fact that the vector $P + PA$ points *toward* the origin in the left-hand figure.

processes. The vector joining this point to the origin is then the best solution obtained using the construction technique. A similar exercise when performed using the last four amplitudes in Table II gives a solution for P . (Note that the only unknown quantity here is P , since $P + PA$ has already been determined independently.) Fig. 1 shows the construction technique for obtaining $P + PA$, while Fig. 2 shows it for P .

The minimum χ^2 obtained for the fit to extract P was found to be much larger than what is expected for a fair fit. In Fig. 2, the construction technique shows that there is no clear region of overlap of the circles implying that we do not have a self-consistent solution, as we do in the case of $P + PA$. However, the extraction method for P uses D_s^+ decay-rates. Although one reason for not finding a self-consistent solution for P could be the need to find a different parametrization of SU(3) breaking in these decays, since the relevant D_s^+ decay rates have large experimental errors it is difficult to study SU(3) breaking using these decays.

Finally we note that in this section we have completely neglected all effects of CP violation. This was justified on the basis that for amplitude studies, the highly CKM-suppressed term P_b may be ignored. Notice that the $P + PA$ terms are proportional to $V_{cs}^* V_{us}$. Although in cases such as $D^0 \rightarrow K^+ K^-$ this term has the same weak-phase as the relevant tree-level topology (in which case there is no CP asymmetry in the absence of P_b), this is not true for example in the case of $D^0 \rightarrow \pi^+ \pi^-$ where the tree-level diagrams are proportional to $V_{cd}^* V_{ud}$. The tiny weak-phase difference between $V_{cd}^* V_{ud}$ and $V_{cs}^* V_{us}$ should give rise to a non-zero CP asymmetry in such cases. Toward the end of Sec. IIIB, however, we shall argue that a direct CP asymmetry arising from this tiny phase difference is at least an order of magnitude smaller than the observed CP asymmetries and hence may be neglected since the relevant experimental error bars are currently much larger than ten percent.

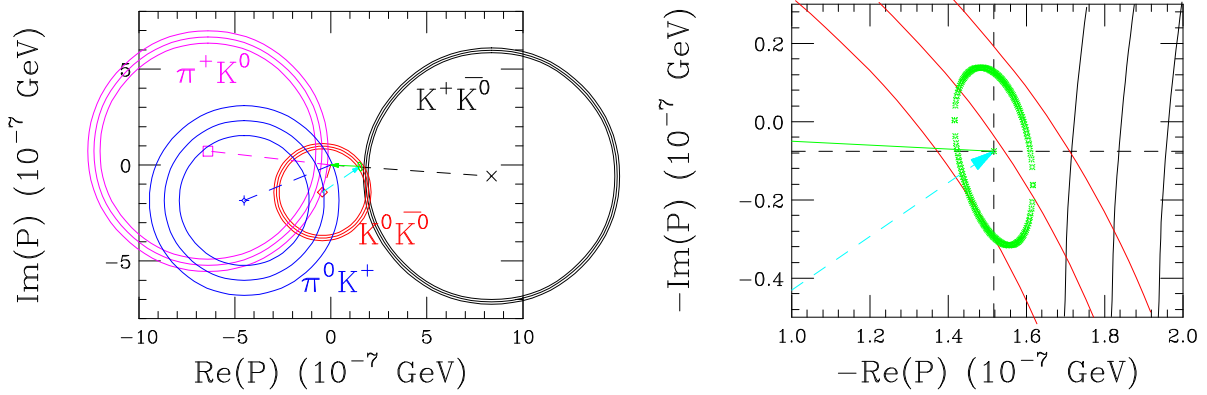


Figure 2: Construction to determine P . The relative sign between the left-hand and (magnified) right-hand panels is due to the fact that the vector P points *toward* the origin in the left-hand figure.

C $D \rightarrow PV$ decays

Flavor-SU(3) techniques are also very useful in studying $D \rightarrow PV$ processes. The related diagrammatics are slightly more complicated since one has to keep track of whether the spectator quark ends up in the P or the V final state. The number of flavor-SU(3) parameters also increases two-fold. Thus in place of T in $D \rightarrow PP$, we now have T_P and T_V in $D \rightarrow PV$, where the subscript refers to the final state in which the spectator quark ended up. Fortunately, there are also many more observable branching fractions. $D \rightarrow PV$ processes were studied in great detail in Refs. [27, 29]. It was found in Ref. [29] that under simple assumptions there are 12 discretely different solutions for T_P , C_V , E_V , T_V , C_P and E_P that fit the observed branching fractions for CF $D \rightarrow PV$ decays. The discrete ambiguity was resolved by applying these parameters to study SCS $D \rightarrow PV$ decays, thus allowing for the choice of a preferred χ^2 minimum solution.

The flavor-SU(3) parameters extracted from $D \rightarrow PV$ may then be put to test in three-body decays, where the final state has three pseudoscalars, two of which are obtained as a result of decay from an intermediate vector resonance. The Dalitz plots for several $D^0 \rightarrow PV \rightarrow 3P$ processes were studied, and several notable features supporting the validity of a flavor-SU(3) approach were found in Refs. [20]. Here we mention very briefly one of the striking successes of this technique when applied to the $D^0 \rightarrow \pi^+\pi^-\pi^0$ Dalitz plot.

Although the $\pi^+\pi^-\pi^0$ final state gets contributions from $I = 0$, 1, and 2 amplitudes, BABAR found that the $I = 0$ channel dominates the decay process $D^0 \rightarrow \pi^+\pi^-\pi^0$. This conclusion can be reached at simply by looking at the Dalitz plot for the said process. The pions have $I = 1$. The only way to form an $I = 0$ combination of three pions is if the wave function were totally antisymmetric under the interchange of any two pions. On the Dalitz plot this implies that the wave function for an $I = 0$ state must vanish along the symmetry axes shown in Fig. 3. BABAR saw very strong depopulation along the symmetry axes of the Dalitz plot and an isospin analysis confirmed the $I = 0$ dominance [30].

A flavor-SU(3) analysis [31] in terms of $D \rightarrow PV$ amplitudes supports this observation. The relative strong phases between interfering resonance amplitudes obtained through flavor SU(3) allow for almost complete cancellation of the $I = 1$ and 2 amplitudes, leading to

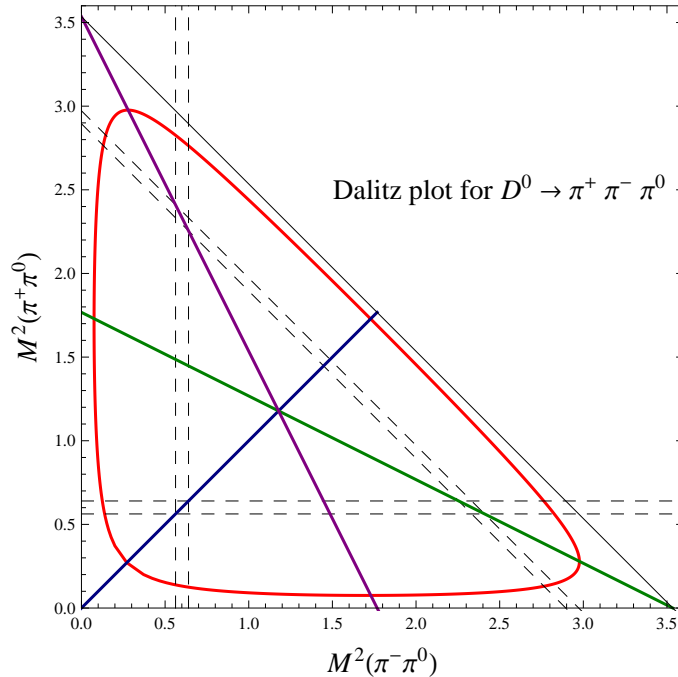


Figure 3: Kinematically allowed region in Dalitz plot for $D^0 \rightarrow \pi^+ \pi^- \pi^0$. Also shown are the symmetry axes in blue, green and purple. Bands between dashed lines represent expected ρ resonance bands.

Table III: Comparison of theory vs. experiment on different isospin amplitude contributions to the $D^0 \rightarrow \pi^+ \pi^- \pi^0$ Dalitz plot.

Channel	Fraction(%) [31]	vs BABAR (%) [30]
$I = 0$	92.9 ± 6.7	94.24 ± 0.40
$I = 1$	4.8 ± 0.3	2.17 ± 0.17
$I = 2$	2.3 ± 0.8	3.58 ± 0.29

an $I = 0$ dominance. In Table III we present a comparison of theory and experiment on different isospin amplitude contributions. This example shows that relative strong phases between amplitudes D decays are obtained fairly successfully using a flavor-SU(3) analysis. Studies of several other Dalitz plots [32–34] show that this technique may also be useful in comparing relative phases between interfering vector resonances and cross-ratios between amplitudes in multiple Dalitz plots. A more detailed discussion of relative phases in $D^0 \rightarrow 3P$ processes may be found in [35].

III Direct CP asymmetries in $D \rightarrow 2P$

A Recent measurements from CDF and LHCb

In our discussion so far we have neglected the CKM-suppressed amplitude P_b . The addition of P_b is expected to have little-to-no effect in case of branching fractions. In this section,

however, we emphasize that this amplitude cannot be completely neglected. P_b may become particularly important in the discussion of direct CP asymmetries in D decays.

The time-integrated CP asymmetry in the process $D^0 \rightarrow f$ is defined as follows:

$$A_{CP} \equiv \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\overline{D}^0 \rightarrow \overline{f})}{\Gamma(D^0 \rightarrow f) + \Gamma(\overline{D}^0 \rightarrow \overline{f})} \quad (20)$$

In the special case that the final state f is a CP eigenstate (such as $\pi^+\pi^-$, K^+K^-), one can express the above as a sum of two terms, direct CP asymmetry for the decay and an indirect CP asymmetry associated with $D^0 - \overline{D}^0$ mixing. The time-integrated CP asymmetry may then be expressed as follows:

$$A_{CP} \approx A_{CP}^{\text{dir}} + \frac{\langle t \rangle}{\tau_D} A_{CP}^{\text{ind}} , \quad (21)$$

where $\langle t \rangle$ is the average decay time in the sample used and τ_D is the true lifetime of the D meson. The indirect CP asymmetry A_{CP}^{ind} is known to be universal to a very good approximation. Thus the difference between the CP asymmetries in $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ is

$$\begin{aligned} \Delta A_{CP} &\equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \\ &= \Delta A_{CP}^{\text{dir}} + \frac{\Delta \langle t \rangle}{\tau_d} A_{CP}^{\text{ind}} . \end{aligned} \quad (22)$$

In the small $\Delta \langle t \rangle$ limit, ΔA_{CP} simply measures the difference in direct CP asymmetries in the two channels $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$.

CP violation in D decays is expected to be small within the Standard Model, owing to the large Cabibbo suppression of the relevant CP-violating amplitudes. The CDF collaboration measured the time-integrated CP violation in $D^0 \rightarrow (\pi^+\pi^-, K^+K^-)$ to be [2]:

$$A_{CP}(D^0 \rightarrow K^+K^-) = (-0.24 \pm 0.22 \pm 0.09)\% , \quad A_{CP}(D^0 \rightarrow \pi^+\pi^-) = (0.22 \pm 0.24 \pm 0.11)\% . \quad (23)$$

We find that the corresponding 90% confidence level limits are:

$$-0.63\% \leq A_{CP}(D^0 \rightarrow K^+K^-) \leq 0.15\% , \quad -0.21\% \leq A_{CP}(D^0 \rightarrow \pi^+\pi^-) \leq 0.65\% , \quad (24)$$

which are consistent with a no-CP violation hypothesis. However, a recent LHCb measurement [3] found 3.5σ evidence for direct CP violation in D^0 decays by measuring the difference between CP asymmetries in the two processes:

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = [-0.82 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})]\% . \quad (25)$$

This result was found to be consistent with the individual time-dependent asymmetry measurements from CDF. By knowing the average decay time in samples for both processes, the CDF collaboration reanalysed their data and also found evidence for direct CP violation at a similar, fraction-of-a-percent level. (The indirect CP asymmetry is found to be of the order of 10^{-4} , so that for small decay time acceptances, the time-integrated asymmetry is close to the direct CP asymmetry.) The combination of the CDF and LHCb results, assuming fully uncorrelated uncertainties, was obtained by the CDF collaboration [4]:

$$\Delta A_{CP}^{\text{dir}} = (-0.67 \pm 0.16)\% ; \quad \Delta A_{CP}^{\text{ind}} = (-0.02 \pm 0.22)\% . \quad (26)$$

The CDF and LHCb results are at least an order of magnitude larger than the natural SM prediction. This has motivated many authors to offer methods of reconciliation both within the SM as well as beyond.

Although the SM is believed to naturally predict a small value of $\Delta A_{CP}^{\text{dir}}$, an order of magnitude enhancement in hadronic matrix elements associated with P_b is not unlikely. In fact, that non-perturbative effects may enhance penguin amplitudes in SCS D decays, similar to the observed $\Delta I = 1/2$ enhancement in $K \rightarrow \pi\pi$, was pointed out by Golden and Grinstein more than two decades ago in Ref. [1]. This is not surprising, since we have evidence for enhancement in the exchange amplitude which is expected to be formally power-suppressed by the mass of the charm quark (m_c). The charm quark mass is not far above Λ_{QCD} . Thus there can be large corrections to such formally power-suppressed terms. A full non-perturbative calculation to extract P_b , however, is extremely difficult and is often associated with sizable uncertainties.

Assuming such enhancements are possible, in the following section, we phenomenologically constrain the magnitude and strong phase of the CP-violating penguin using the CDF and LHCb measurements. Using the extracted magnitude and strong phase of the penguin P_b we then predict direct CP asymmetries in other D^0 and D^+ decays to two pseudoscalars.

B Direct CP asymmetries using flavor SU(3)

The amplitude for a general SCS D decay to a final state f may be expressed in the form:

$$\begin{aligned} \mathcal{A}(D \rightarrow f) &= T_f + P_b \\ &= |T_f| e^{i\phi_T^f} \left(1 + \frac{|P_b|}{|T_f|} e^{i(\delta - \phi_T^f - \gamma)} \right), \end{aligned} \quad (27)$$

where $|T_f|$ and ϕ_T^f are respectively the magnitude and strong phase of the CP-conserving part of the amplitude, while δ and $-\gamma$ are respectively the strong and weak phases of the CP-violating term P_b , which we have written as $P_b = |P_b| e^{i(\delta - \gamma)}$. We have assumed that the weak-phase difference between the CP-violating term (proportional to $V_{cb}^* V_{ub}$) and the CP-conserving term (proportional to $V_{cs}^* V_{us}$) is $-\gamma$, where $\gamma = 77^\circ$ is the angle in the standard CKM unitarity triangle. (The deviation of the weak-phase difference between $V_{cb}^* V_{ub}$ and $V_{cs}^* V_{us}$ from $-\gamma$ consists of $\mathcal{O}(\lambda^4)$ terms and may be neglected compared to γ). In writing Eq. (27), we have also assumed that a PA_b contribution to the relevant CP asymmetries may be neglected compared to the P_b contribution.

In order to obtain the CP-conjugate amplitude $\overline{\mathcal{A}}(\overline{D} \rightarrow f)$ one simply changes the sign of the weak phase, which is done by changing $-\gamma$ to γ . We may now construct the direct CP asymmetries for $D \rightarrow f$ as follows:

$$\begin{aligned} A_{CP}(f) &= \frac{|\mathcal{A}|^2 - |\overline{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2} \\ &= \frac{2(|P_b|/|T_f|) \sin \gamma \sin(\delta - \phi_T^f)}{1 + (|P_b|/|T_f|)^2 + 2(|P_b|/|T_f|) \cos \gamma \cos(\delta - \phi_T^f)} \\ &\approx 2(|P_b|/|T_f|) \sin \gamma \sin(\delta - \phi_T^f), \end{aligned} \quad (28)$$

where in the final line we have neglected higher order terms in $|P_b|/|T_f|$, since this quantity is much smaller than one. Notice that the overall strong phase of the CP-conserving

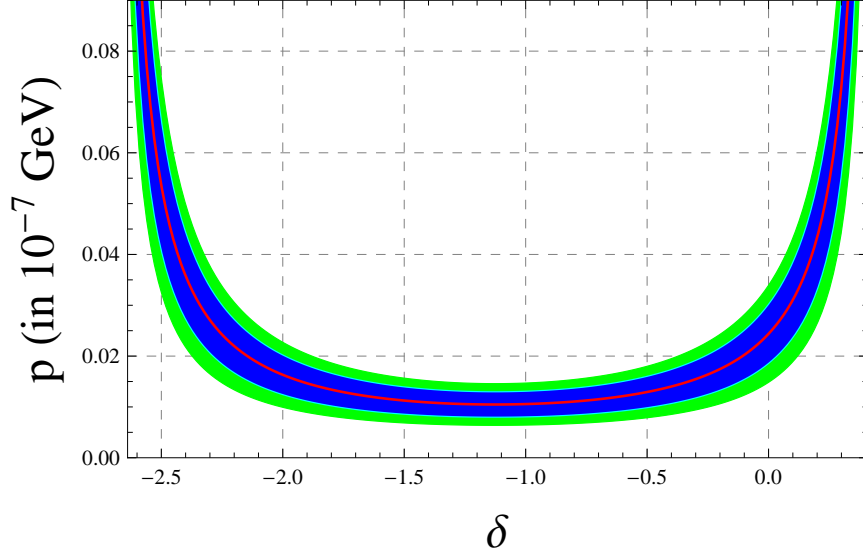


Figure 4: $p \equiv |P_b|$ and δ allowed by the measured range of ΔA_{CP} . The (red) line represents the central value, while inner (blue) and outer (green) bands respectively represent 68% confidence level (1σ) and 90% confidence level (1.64σ) regions based on error in ΔA_{CP} .

term can only be obtained from the fits up to a common sign ambiguity. However, the CP asymmetries are approximately invariant under the joint transformations $\phi_T^f \rightarrow -\phi_T^f$ and $\delta \rightarrow \pi - \delta$ as long as $|P_b|/|T_f|$ is small compared to one. The joint LHCb – CDF measurement of $\Delta A_{CP}^{\text{dir}}$ (26) may now be expressed as a constraint involving two unknown parameters, namely $|P_b|$ and δ . In addition the CDF measurements (24) for the individual asymmetries may be used to obtain upper and lower bounds on δ .

In Fig. 4 we plot the allowed range of $p \equiv |P_b|$ (up to 90% confidence level regions consistent with Eq. (26) as a function of δ in the range $-2.64 \leq \delta \leq 0.41$ determined by the CDF upper and lower bounds on the individual CP asymmetries in $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$ (24). For a large range of δ , we find that $|P_b| \sim 0.01 \times 10^{-7}$ GeV, thus indicating that the ratio $|P_b|/|T_f| \sim 1.2 \times 10^{-3}$ is indeed small compared to one. (We have used $|T_f| \approx |\mathcal{A}(D^0 \rightarrow K^+ K^-)| = 8.46 \times 10^{-7}$ GeV.) It is interesting also to look at the ratio of the reduced matrix elements of tree and penguin topologies (defined similarly to Eq. (11)) which may be obtained as follows:

$$\begin{aligned} \frac{|P_b|}{|T_f|} &= \frac{|V_{cs}^* V_{us}|}{|V_{cb}^* V_{ub}|} \frac{|P_b|}{|T_f|} \\ &\approx 1.5 \times 10^3 \frac{|P_b|}{|T_f|} \\ &\sim 2, \end{aligned} \tag{29}$$

where we have used Particle Data Group values for the CKM matrix elements.

Let us now revisit the question raised at the end of Sec. IIB. In our conventions, the weak phase difference between $V_{cd}^* V_{ud}$ and $V_{cs}^* V_{us}$ differs from π by a tiny amount, which may give rise to a non-zero direct CP asymmetry in the decay $D^0 \rightarrow \pi^+ \pi^-$, even in the absence of the CP-violating penguin P_b . This decay amplitude may be expressed as follows:

$$\mathcal{A}(D^0 \rightarrow \pi^+ \pi^-) = V_{cd}^* V_{ud} (T_\pi + E) + (P + PA)$$

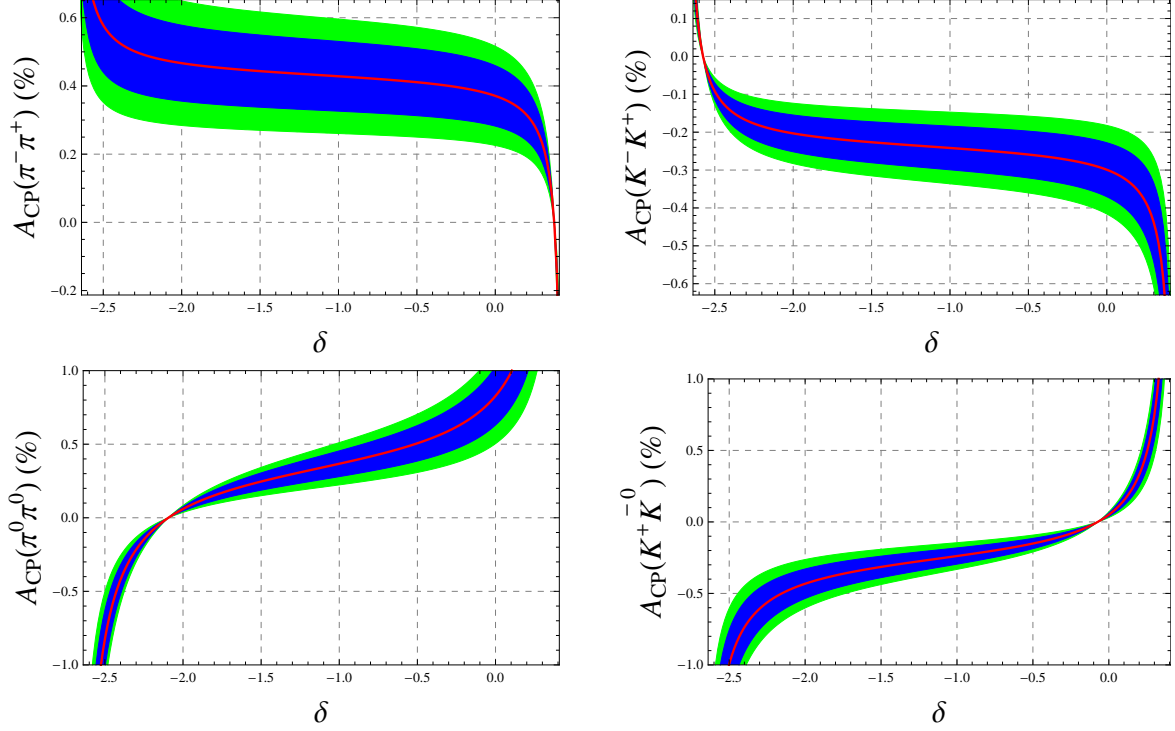


Figure 5: Direct CP asymmetry ($A_{CP}(f)$) in various D^0 and D^+ decay modes plotted as a function of the allowed values of δ . The (red) lines represent the central values, while inner (blue) and outer (green) bands respectively represent 68% confidence level (1σ) and 90% confidence level (1.64σ) regions based on error in ΔA_{CP} .

$$= V_{cd}^* V_{ud} (T_\pi + E) + V_{cs}^* V_{us} (\mathcal{P} + \mathcal{P}\mathcal{A}) , \quad (30)$$

where $\mathcal{P} = \mathcal{P}_s - \mathcal{P}_d$ and $\mathcal{P}\mathcal{A} = \mathcal{P}\mathcal{A}_s - \mathcal{P}\mathcal{A}_d$. The weak phase difference (ϕ) between $V_{cs}^* V_{us}$ and $V_{cd}^* V_{ud}$ is a tiny bit different from π :

$$\sin \phi = - \frac{|V_{cb}| |V_{ub}|}{|V_{cs}| |V_{us}|} \sin \gamma \sim - 6.8 \times 10^{-4} . \quad (31)$$

However, the ratio of reduced penguin matrix elements to tree ones, in this case, is at least an order of magnitude smaller:

$$\frac{|\mathcal{P} + \mathcal{P}\mathcal{A}|}{|\mathcal{T}_f|} \approx \frac{|P + P\mathcal{A}|}{|T_f|} \sim 0.2 \quad (32)$$

Thus the associated CP asymmetry is also an order of magnitude smaller and we can ignore this contribution.

Now that we have constrained $|P_b|$ as a function of δ , we may use it to explore direct CP asymmetries in other D^0 and D^+ processes. In Fig. 5, we use Eq. (28) and values of ϕ_T^f from Table II, to plot the direct CP asymmetries in the processes $D^0 \rightarrow (\pi^+ \pi^-, K^+ K^-, \pi^0 \pi^0)$ and $D^+ \rightarrow K^+ \bar{K}^0$ as a function of the strong phase δ , within the range allowed by the CDF bounds. The CP asymmetries for the final states $\pi^+ \pi^-$ and $K^+ K^-$ are found to follow the central values of the CDF measurements quoted in Eq. (24). The $\pi^+ \pi^-$ CP asymmetry is found to be positive, while the $K^+ K^-$ CP asymmetry is found to be negative

for a large range of allowed δ values. In order to be able to pinpoint δ , however, we need more precise measurements of the individual asymmetries in these two channels. We also note the correlation between the CP asymmetries in $\pi^0\pi^0$ and $K^+\bar{K}^0$. The former is found to be positive while the later is found to be negative, for a large range of δ . The best experimental value of the CP asymmetry in $K^+\bar{K}^0$, from the Belle experiment [36], has large error bars and is consistent with zero.

Notice that amplitudes not involving P_b ($D^0 \rightarrow K^0\bar{K}^0$ and $D^+ \rightarrow \pi^+\pi^0$) automatically have $A_{CP}^{\text{dir}} = 0$. One can generate a non-zero direct CP asymmetry in $D^0 \rightarrow K^0\bar{K}^0$ by including a PA_b contribution, but it is considerably harder to generate a large CP asymmetry in $D^+ \rightarrow \pi^+\pi^0$. Due to Bose statistics the $\pi^+\pi^0$ state has $I = 2$ and thus can't get contributions from $\Delta I = 1/2$ penguin topologies. (There may still be electroweak-penguin contributions. However these are expected to be too small in D decays to give rise to a percent level CP asymmetry.)

D_s^+ decay rates have large error bars, and measurements of CP asymmetries in D_s^+ processes are as yet unavailable. The D_s^+ CP asymmetry discussion has therefore been left out of the present analysis.

IV Conclusions

In this talk we explored the possibility of using flavor-SU(3) symmetry to study branching ratios and direct CP asymmetries in D^0 and D^+ decays. Based on our study of branching ratios we may arrive at the following conclusions:

- The flavor-SU(3) framework works fairly well with CF D decays. A χ^2 minimization fit to extract the parameters yields a low value χ^2 minimum.
- Measured branching fractions of SCS D^0 decays to $\pi^+\pi^-$ and K^+K^- deviate considerably from flavor-SU(3) predictions; factorizable SU(3) breaking in “Tree” amplitudes does not provide a satisfactory explanation.
- We propose a model for SU(3) breaking in SCS $D^0 \rightarrow PP$ decays, which is realized through an absence of GIM cancellation in penguin topologies.
- D^0 decays seem to follow the proposed SU(3) breaking scheme. However, it seems quite early to comment on D^+ and D_s^+ decays, where the error bars are quite large.
- $D \rightarrow PV$ decays are interesting, but these processes involve many more parameters and there are not enough data available.
- Flavor SU(3) is successful in explaining $I = 0$ dominance in the $D^0 \rightarrow \pi^0\pi^+\pi^-$ Dalitz plot; cross ratios in several other Dalitz plots seem to agree with flavor-SU(3) predictions.

In the second part of the talk we applied our results from the study of branching ratios in D decays to explore the possibility of explaining recent CP violation measurements in SCS D decays and also predicting CP violation in other D^0 and D^+ decays. From this discussion we may infer the following:

- The recent LHCb and CDF ΔA_{CP} measurements can be explained by considering an enhanced CP-violating penguin, something that is not unusual to expect within the framework of the SM.
- Given the present experimental limits, the strong phase (δ) of the CP-violating penguin amplitude is still fairly unconstrained. In order to pinpoint δ , a more precise determination of the individual CP asymmetries in the $\pi^+\pi^-$ and K^+K^- final states is necessary. In turn this will lead to a better prediction of CP asymmetries in several other final states.
- We predict A_{CP} in $D^+ \rightarrow K^+\overline{K}^0$ and $D^0 \rightarrow \pi^0\pi^0$; these CP asymmetries seem to be correlated; $K^+\overline{K}^0$ is negative while $\pi^0\pi^0$ is positive for a large range of δ .
- In the model that we presented $A_{CP} = 0$ in $D^0 \rightarrow K^0\overline{K}^0$ and $D^+ \rightarrow \pi^+\pi^0$; a non-zero A_{CP} in the former case may be explained by introducing a CP-violating penguin topology of the annihilation type (PA_b).
- $A_{CP} \neq 0$ in $D^+ \rightarrow \pi^+\pi^0$ needs new dynamics with both weak and strong phases different from the SM tree-level topologies.

In our present study we left out a wide variety of final states, due to lack of experimental data as well as theoretical understanding. The SCS D^0 decays with an η or an η' in the final state also call for OZI-suppressed singlet-exchange and -annihilation topologies, which were not studied. Furthermore, CP asymmetries in D meson decays to a pseudoscalar and a vector present a whole new subject. With future measurements from LHCb and super-B factories we hope that our understanding of the SM at low energies will get even better.

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